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SYSTEM FOR RADIALLY EXPANDING TUBULAR MEMBERS

Cross Reference to Related Applications

[001] The present application is the National Stage patent application for PCT patent application serial number PCT/US2003/038550, attorney docket number 25791.157.02, filed on 12/04/2003, which claimed the benefit of the filing dates of (1) U.S. provisional patent application serial no. 60/431,184, attorney docket no 25791.157, filed on 12/5/2002, the disclosures of which are incorporated herein by reference.

[002] The present application is related to the following: (1) U.S. patent application serial no. 09/454,139, attorney docket no. 25791.03.02, filed on 12/3/1999, (2) U.S. patent application serial no. 09/510,913, attorney docket no. 25791.7.02, filed on 2/23/2000, (3) U.S. patent application serial no. 09/502,350, attorney docket no. 25791.8.02, filed on 2/10/2000, (4) U.S. patent no. 6,328,113, (5) U.S. patent application serial no. 09/523,460, attorney docket no. 25791.11.02, filed on 3/10/2000, (6) U.S. patent application serial no. 09/512,895, attorney docket no. 25791.12.02, filed on 2/24/2000, (7) U.S. patent application serial no. 09/511,941, attorney docket no. 25791.16.02, filed on 2/24/2000, (8) U.S. patent application serial no. 09/588,946, attorney docket no. 25791.17.02, filed on 6/7/2000, (9) U.S. patent application serial no. 09/559,122, attorney docket no. 25791.23.02, filed on 4/26/2000, (10) PCT patent application serial no. PCT/US00/18635, attorney docket no. 25791.25.02, filed on 7/9/2000, (11) U.S. provisional patent application serial no. 60/162,671, attorney docket no. 25791.27, filed on 11/1/1999, (12) U.S. provisional patent application serial no. 60/154,047, attorney docket no. 25791.29, filed on 9/16/1999, (13) U.S. provisional patent application serial no. 60/159,082, attorney docket no. 25791.34, filed on 10/12/1999, (14) U.S. provisional patent application serial no. 60/159,039, attorney docket no. 25791.36, filed on 10/12/1999, (15) U.S. provisional patent application serial no. 60/159,033, attorney docket no. 25791.37, filed on 10/12/1999, (16) U.S. provisional patent application serial no. 60/212,359, attorney docket no. 25791.38, filed on 6/19/2000, (17) U.S. provisional patent application serial no. 60/165,228, attorney docket no. 25791.39, filed on 11/12/1999, (18) U.S. provisional patent application serial no. 60/221,443, attorney docket no. 25791.45, filed on 7/28/2000, (19) U.S. provisional patent application serial no. 60/221,645, attorney docket no. 25791.46, filed on 7/28/2000, (20) U.S. provisional patent application serial no. 60/233,638, attorney docket no. 25791.47, filed on 9/18/2000, (21) U.S. provisional patent application serial no. 60/237,334, attorney docket no. 25791.48, filed on 10/2/2000, (22) U.S. provisional patent application serial no. 60/270,007, attorney docket no. 25791.50, filed on 2/2012001, (23) U.S. provisional patent application serial no. 60/262,434, attorney docket no. 25791.51, filed on 1/17/2001, (24) U.S. provisional patent application serial

no. 60/259,486, attorney docket no. 25791.52, filed on 1/3/2001, (25) U.S. provisional patent application serial no. 60/303,740, attorney docket no. 25791.61, filed on 7/6/2001, (26) U.S. provisional patent application serial no. 60/313,453, attorney docket no. 25791.59, filed on 8/20/2001, (27) U.S. provisional patent application serial no. 60/317,985, attorney docket no. 25791.67, filed on 9/6/2001, (28) U.S. provisional patent application serial no. 60/318,021, attorney docket no. 25791.58, filed on 9/7/2001, (29) U.S. provisional patent application serial no. 60/3318,386, attorney docket no. 25791.67.02, filed on 9/10/2001, (30) U.S. provisional patent application serial no. 60/326,886, attorney docket no. 25791.60, filed on 1013/2001, (31) U.S. utility patent application serial no. 09/969,922, attorney docket no. 25791.69, filed on 10/3/2001, (32) U.S. provisional patent application serial no. 60/338,996, attorney docket no. 25791.87, filed on 11/12/2001, (33) U.S. provisional patent application serial no. 60/339,013, attorney docket no. 25791.88, filed on 11/12/2001, (34) U.S. utility patent application serial no. 10/016,467, attorney docket no. 25791.70, filed on 12/10/2001, (35) U.S. provisional patent application serial no. 60/343,674, attorney docket no. 25791.68, filed on 12127/2001, (36) U.S. provisional patent application serial no. 60/346,309, attorney docket no 25791.92, filed on 1/712002, (37) U.S. provisional patent application serial no. 601357,372, attorney docket no. 25791.71, filed on 2/15/2002, (38) U.S. provisional patent application serial no. 60/363,829, attorney docket no. 25791.95, filed on 3/1312002, (39) U.S. provisional patent application serial no. 60/372,048, attorney docket no. 25791.93, filed on 4/12/2002, (40) U.S. provisional patent application serial no. 60/372,632, attorney docket no. 25791.101, filed on 4/15/2002, (41) U.S. provisional patent application serial no. 60/380,147, attorney docket no. 25791.104, filed on 5/6/2002, (42) U.S. provisional patent application serial no. 60/383,917, attorney docket no. 25791.89, filed on 5/2912002, (43) U.S. provisional patent application serial no. 60/387,486, attorney docket no. 25791.107, filed on 6/10/2002, (44) U.S. provisional patent application serial no. 60/387,961, attorney docket no. 25791.108, filed on 611212002, (45) U.S. provisional patent application serial no. 60/391,703, attorney docket no. 25791.90, filed on 6/26/2002, (46) U.S. provisional patent application serial no. 60/397,284, attorney docket no. 25791.106, filed on 7/19/2002, (47) U.S. provisional patent application serial no. 60/398,061, attorney docket no. 25791.110, filed on 7/24/2002, (48) U.S. provisional patent application serial no. 60/399,240, attorney docket no. 25791.111, filed on 7/2912002, (49) U.S. provisional patent application serial no, 601405,610, attorney docket no. 25791.119, filed on 8/2312002, (50) U.S. provisional patent application serial no. 60/405,394, attorney docket no. 25791.120, filed on 8/2312002, (51) U.S. provisional patent application serial no. 60/407,442, attorney docket no. 25791.125, filed on 8/30/2002, (52) U.S. provisional patent application serial no. 60/412,542, attorney

docket no. 25791.102, filed on 9/20/2002, (53) U.S. provisional patent application serial no. 60/412,177, attorney docket no. 25791.117, filed on 9/20/2002, (54) U.S. provisional patent application serial no. 60/412,653, attorney docket no. 25791.118, filed on 9/20/2002, (55) U.S. provisional patent application serial no. 601412,544, attorney docket no. 25791.121, filed on 9/20/2002, (56) U.S. provisional patent application serial no. 60/412,187, attorney docket no. 25791.128, filed on 9/20/2002, (57) U.S. provisional patent application serial no. 60/412,196, attorney docket no. 25791.127, filed on 9/20/2002, (58) U.S. provisional patent application serial no. 60/412,487, attorney docket no. 25791.112, filed on 9/20/2002, (59) U.S. provisional patent application serial no. 601412,488, attorney docket no. 25791.114, filed on 9/20/2002, (60) U.S. provisional patent application serial no. 60/412,371, attorney docket no. 25791.129, filed on 9/20/2002, (61) PCT patent application serial no. PCT/US02/36157, attorney docket no. 25791.87.02, filed on 11/12/2002, and (62) PCT patent application serial no. PCT/US02/36267, attorney docket no. 25791.88.02, filed on 11/12/2002, the disclosures of which are incorporated herein by reference.

Brief Description of the Drawings

[003] Fig. 1a is a fragmentary cross sectional illustration of an embodiment of a system for radially expanding and plastically deforming an expandable tubular member.

[004] Fig. 1b is a fragmentary cross sectional illustration of the system of Fig. 1a during the radial expansion and plastic deformation of the expandable tubular member.

[005] Fig. 1c is a graphical illustration of exemplary experimental testing of the system of Fig. 1a.

[006] Fig. 2a is fragmentary cross sectional illustration of another embodiment of a system for radially expanding and plastically deforming a tubular member.

[007] Fig. 2b is a fragmentary cross sectional illustration of the system of Fig. 2a during the radial expansion and plastic deformation of the expandable tubular member.

[008] Fig. 3a is fragmentary cross sectional illustration of another embodiment of a system for radially expanding and plastically deforming a tubular member.

[009] Fig. 3b is fragmentary cross sectional illustration of another embodiment of a system for radially expanding and plastically deforming a tubular member.

[0010] Fig. 4a is fragmentary cross sectional illustration of another embodiment of a system for radially expanding and plastically deforming a tubular member.

[0011] Fig. 4b is fragmentary cross sectional illustration of another embodiment of a system for radially expanding and plastically deforming a tubular member.

[0012] Fig. 5a is a graphical illustration of an exemplary embodiment of the generation of vibratory energy in one or more planes.

[0013] Fig. 5b is a graphical illustration of an exemplary embodiment of the generation of vibratory energy having one or more center frequencies of vibratory energy.

[0014] Fig. 6 is a flow chart illustration of an exemplary embodiment of a method for characterizing the operational characteristics of a radial expansion system as a function of the plane and/or frequency content of the vibratory energy.

Detailed Description of the Illustrative Embodiments

[0015] The present illustrative embodiments relate generally to radially expanding and plastically deforming expandable tubulars and more particularly to reducing the required expansion forces during the radial expansion and plastic deformation of the expandable tubulars and/or enhancing residual stresses in the expandable tubulars after the radial expansion and plastic deformation of the expandable tubulars.

[0016] Referring initially to Fig. 1a, a system 10 for radially expanding and plastically deforming an expandable tubular member includes a tubular support member 12 that defines an internal passage 12a. An end of the tubular support member 12 is coupled to an end of an expansion cone 14 that defines an internal passage 14a and include an outer conical expansion surface 14b. A conventional vibrator 16 is coupled to the tubular support member 12 proximate one side of the expansion cone 14. In an exemplary embodiment, the vibrator 16 is a conventional fluid powered and adjustable vibratory hammer device commercially available from Smith International.

[0017] An expandable tubular member 18 that includes a lower tubular portion 18a, an upper tubular portion 18b, and an intermediate tapered tubular portion 18c is supported by the outer conical expansion surface 14b of the expansion cone 14. A shoe 20 that defines a valveable passage 20a is coupled to an end of the lower tubular portion 18a of the expandable tubular member 18. One or more compressible sealing members 22 are coupled to the exterior surface of the upper tubular portion 18b of the expandable tubular member 18.

[0018] In several exemplary embodiments, the outer expansion surface 14b of the expansion cone 14 may include conical, spherical, elliptical, and/or hyperbolic actuate segments that may or may not include faceted segments.

[0019] In an exemplary embodiment, during operation, the system 10 is initially positioned within a welbore 24 that traverses a subterranean formation 26. A fluidic material 30 may then be injected through the passages 12a, 14a, 20a, of the tubular support member 12, expansion

cone 14, and shoe 20, respectively, in order to determine the proper functioning of the passages.

[0020] As illustrated in Fig. 1b, a ball 30, or other equivalent device, may then be introduced into the injection of the fluidic material 30 to thereby position the ball within the valveable passage 20a of the shoe 20. In this manner, fluid flow through the valveable passage 20a of the shoe 20 may be blocked. Continued injection of the fluidic material 30 following the placement of the ball within the valveable passage 20a of the shoe 20 will then pressurize the interior of the expandable tubular member 18 below the expansion cone 14. As a result, the expansion cone 14 will be displaced upwardly relative to the expandable tubular member 18 thereby causing the conical expansion surface 14b of the expansion cone 14 to radially expand and plastically deform the expandable tubular member 18.

[0021] In an exemplary embodiment, during the radial expansion and plastic deformation of the expandable tubular member 18, the vibrator 16 is operated to thereby generate vibratory energy. As a result, in an exemplary embodiment, the operational pressure of the injected fluid 28 required during the radial expansion of the tubular member 18 is reduced thereby increasing the operational efficiency of the system 10.

[0022] In an exemplary experimental test of the system 10, a comparison was made between the operation of the system, with and without the vibrator 16. The following table summarizes the comparative results of the exemplary experimental test of the system 10, with and without the vibrator 16:

Operational Variables During The Radial Expansion Of The Tubular Member 18 Using The System 10	**Operation of the System 10 to Radially Expand the Tubular Member 18, Without the Vibrator 16**	**Operation of the System 10 to Radially Expand the Tubular Member 18, With the Vibrator 16**
Operating Pressure of the Injected Fluid 28	3,700 psi	2,880 psi
Expansion Distance	13 inches	70 inches
Expansion Speed	360 ft/hour	223/hour
Operating Frequency Of The Vibrator 16	N/A	approximately 40 Hz

[0023] Thus, in an exemplary experimental test of the system 10, with and without the vibrator 16, the use of the vibrator reduced the operating pressure of the injected fluid 28 during the radial expansion of the tubular member 18 by approximately 25%. This was an unexpectedly large reduction in the operating pressure of the injected fluid 28 provided by the operation of the

vibrator 16. As illustrated in Fig. 1c, exemplary experimental testing of the system 10 indicated that the required operating pressure of the injected fluid 28 was a minimum at an operating frequency for the vibrator 16 of approximately 40 Hz. In an exemplary embodiment, the optimal operating frequency of the vibrator 16 for the system 10 may vary as a function of the precise operating conditions, geometry, and material properties of the system 10. Thus, an optimal operating frequency may be empirically determined for any given embodiment, or variant, of the system 10.

[0024] Thus, in an exemplary experimental implementation of the system 10, the operation of the system with the vibrator 16 reduced the required operating pressure of the injected fluidic material 28 thereby enhancing the operational efficiency of the system and reducing the required radial expansion forces. Based upon the exemplary experimental results of the operation of the system 10, as well as theoretical analysis of the operation of the system, the reduction in the required expansion forces necessary to radially expand and plastically deform the tubular member 18 is due to at least one or more of the following phenomena: 1) the vibratory energy generated by the vibrator 16 reduces the contact and/or dynamic friction coefficient between the interior surface of the tubular member and the tapered exterior surface 14b of the expansion cone 14; and/or 2) the vibratory energy generated by the vibrator is absorbed by the tubular and thereby increases the plasticity and formability of the tubular member. Furthermore, an additional benefit of the system 10 with the vibrator 16 is that the need for a lubricating material between the interior surface of the tubular member and the tapered exterior surface 14b of the expansion cone 14 may be reduced.

[0025] Referring to Fig. 2a, a system 100 for radially expanding and plastically deforming an expandable tubular member is provided that is substantially identical in design and operation to the system 10, except as described below. The system 100 further includes a tubular support member 102 that defines a passage 102a and a vibrator 104 that is positioned proximate another end of the expansion cone 14. In an exemplary embodiment, the vibrator 104 is a conventional fluid powered and adjustable vibratory hammer device commercially available from Smith International.

[0026] In an exemplary embodiment, during operation, the system 100 is initially positioned within a welbore 24 that traverses a subterranean formation 26. A fluidic material 30 may then be injected through the passages 12a, 14a, 102a, and 20a, of the tubular support member 12, expansion cone 14, the tubular support member 102, and the shoe 20, respectively, in order to determine the proper functioning of the passages.

[0027] As illustrated in Fig. 2b, a ball 30, or other equivalent device, may then be introduced into the injection of the fluidic material 30 to thereby position the ball within the valveable passage 20a of the shoe 20. In this manner, fluid flow through the valveable passage 20a of the shoe 20 may be blocked. Continued injection of the fluidic material 30 following the placement of the ball within the valveable passage 20a of the shoe 20 will then pressurize the interior of the expandable tubular member 18 below the expansion cone 14. As a result, the expansion cone 14 will be displaced upwardly relative to the expandable tubular member 18 thereby causing the conical expansion surface 14b of the expansion cone 14 to radially expand and plastically deform the expandable tubular member 18.

[0028] In an exemplary embodiment, during the radial expansion and plastic deformation of the expandable tubular member 18, the vibrators 16 and/or 104 are operated to thereby generate vibratory energy. As a result, the required operational pressure of the injected fluid 28 may be reduced thereby increasing the operational efficiency of the system 100.

[0029] Referring to Fig. 3a, a system 200 for radially expanding and plastically deforming an expandable tubular member includes a conventional rotary expansion device 202 that is coupled to an end of a support member 204. In several exemplary embodiment, the rotary expansion device 202 is provided substantially as disclosed in one or more of the following: U.S. Patent Publication US 2003/0024711, U.S. Patent Publication US 2002/0195256, U.S. Patent Publication US 2002/0195252, U.S. Patent Publication US 2002/0185274, U.S. Patent Publication US 2002/0139540, U.S. Patent No. 6,425,444, U.S. Patent No. 6,543,552, U.S. Patent No. 6,527,049, and/or U.S. Patent No. 6,457,532, the disclosures of which are incorporated herein by reference. In several exemplary embodiments, the rotary expansion device 202 includes, or incorporates at least some of the elements of, one or more of the commercially available rotary expansion devices available from Weatherford International.

[0030] In an exemplary embodiment, a vibrator 206 is coupled to the support member 204 proximate the rotary expansion device 202. In an exemplary embodiment, the vibrator 206 is a conventional fluid powered and adjustable vibratory hammer device commercially available from Smith International.

[0031] An expandable tubular member 208 that includes a lower tubular portion 208a, an upper tubular portion 208b, and an intermediate tapered tubular portion 208c is coupled to the rotary expansion device 202.

[0032] In an exemplary embodiment, during operation of the system 200, the system is initially positioned within a welbore 24 that traverses a subterranean formation 26. The rotary

expansion device 202 is then operated in a conventional manner to thereby radially expand and plastically deform the expandable tubular member 18.

[0033] In an exemplary embodiment, during the radial expansion and plastic deformation of the expandable tubular member 18, the vibrator 206 is operated to thereby generate vibratory energy. As a result, the required expansion forces may be reduced thereby increasing the operational efficiency of the system 200.

[0034] Referring to Fig. 3b, a system 300 for radially expanding and plastically deforming an expandable tubular member is provided that is substantially identical to the system 200, except as described below. In an exemplary embodiment, the system 300 further includes a vibrator 302 positioned proximate another side of the rotary expansion device 202. In an exemplary embodiment, the vibrator 302 is a conventional fluid powered and adjustable vibratory hammer device commercially available from Smith International.

[0035] In an exemplary embodiment, during operation of the system 300, the system is initially positioned within a welbore 24 that traverses a subterranean formation 26. The rotary expansion device 202 is then operated in a conventional manner to thereby radially expand and plastically deform the expandable tubular member 18.

[0036] In an exemplary embodiment, during the radial expansion and plastic deformation of the expandable tubular member 18, the vibrators 206 and/or 302 are operated to thereby generate vibratory energy. As a result, the required expansion forces are reduced thereby enhancing the operational efficiency of the system 300.

[0037] Referring to Fig. 4a, a system 400 for radially expanding and plastically deforming an expandable tubular member includes a conventional actuator 402 that is coupled to an end of a conventional expansion cone 404 that includes a conical outer expansion surface 404a. The actuator 402 is also coupled to a conventional locking device 406 that is adapted to controllably engage a lower portion 408a of an expandable tubular member 408 that also includes an upper portion 408b and a tapered intermediate portion 408c. A conventional vibrator 410 is also coupled to another end of the expansion cone 404. In an exemplary embodiment, the vibrator 410 is a conventional fluid powered and adjustable vibratory hammer device commercially available from Smith International.

[0038] In several exemplary embodiment, the combination of the actuator 402, the expansion cone 404, and/or the locking device 406 provide an expansion tool that is provided substantially as disclosed in one or more of the following: U.S. Patent Publication US 2003/005691, U.S. Patent Publication US 2002/0084070, U.S. Patent Publication US 2002/0079101, U.S. Patent Publication US 2002/0062956, U.S. Patent Publication US 2001/0020532, U.S. Patent No.

6,135,208, U.S. Patent No. 6,446,724, and/or U.S. Patent No. 6,098,717, the disclosures of which are incorporated herein by reference. In several exemplary embodiments, the expansion tool includes, or incorporates at least some of the elements of, one or more of the commercially available expansion devices available from Baker Hughes.

[0039] In an exemplary embodiment, during operation of the system 400, the system is initially positioned within a wellbore 24 that traverses a subterranean formation 26. During the placement of the system 400 within the welbore 24, the expandable tubular member 408 is coupled to the locking device 406. The actuator 402 is then operated in a conventional manner to displace the expansion cone 404 in a direction away from the locking device 406 thereby radially expanding and plastically deforming a portion of the expandable tubular member 408.

[0040] In an exemplary embodiment, during the radial expansion and plastic deformation of the expandable tubular member 408, the vibrator 410 is operated to thereby generate vibratory energy. As a result, the required expansion forces may be reduced thereby enhancing the operational efficiency of the system 400.

[0041] Referring to Fig. 4b, a system 500 for radially expanding and plastically deforming an expandable tubular member is provided that is substantially identical to the system 400, except as described below. In an exemplary embodiment, the system 500 further includes a vibrator 502 positioned proximate another side of the expansion cone 404. In an exemplary embodiment, the vibrator 502 is a conventional fluid powered and adjustable vibratory hammer device commercially available from Smith International.

[0042] In an exemplary embodiment, during operation of the system 500, the system is initially positioned within a wellbore 24 that traverses a subterranean formation 26. During the placement of the system 500 within the welbore 24, the expandable tubular member 408 is coupled to the locking device 406. The actuator 402 is then operated in a conventional manner to displace the expansion cone 404 in a direction away from the locking device 406 thereby radially expanding and plastically deforming a portion of the expandable tubular member 408.

[0043] In an exemplary embodiment, during the radial expansion and plastic deformation of the expandable tubular member 408, the vibrators 410 and/or 502 are operated to thereby generate vibratory energy. As a result, the required expansion forces may be reduced thereby enhancing the operational efficiency of the system 500.

[0044] In an exemplary embodiment, the use of the vibrators, 16, 104, 206, 302, 410, and 502, in the systems, 10, 100, 200, 300, 400, and 500, reduces the expansion forces required to radially expand and plastically deform the tubular members, 18, 208, and 408. The reduction in the required expansion forces necessary to radially expand and plastically deform the tubular

members, 18, 208, and 408, is due to at least one or more of the following phenomena: 1) the vibratory energy generated by the vibrators, 16, 104, 206, 302, 402, and 410, reduce the contact and/or dynamic friction coefficient between the interior surface of the tubular members and the exterior surfaces of the expansion cone 14, the rotary expansion device 202, and the expansion cone 404; and/or 2) the vibratory energy generated by the vibrators is absorbed by the tubular members and thereby increases the plasticity and formability of the tubular members.

[0045] In several alternative embodiments, the vibrator 16 is integral to the expansion cone 14.

[0046] In several alternative embodiments, the vibrator 16 and/or the vibrator 104 is integral to the expansion cone 14.

[0047] In several alternative embodiments, the vibrator 206 is integral to the rotary expansion device 202.

[0048] In several alternative embodiments, the vibrator 206 and/or the vibrator 302 is integral to the rotary expansion device 202.

[0049] In several alternative embodiments, the vibrator 410 is integral to the expansion cone 404.

[0050] In several alternative embodiments, the vibrator 410 and/or the vibrator 502 is integral to the expansion cone 404.

[0051] In several alternative embodiments, the vibrators 16, 104, 206, 302, 410, and/or 502 may be any conventional commercially available device capable of generating vibratory energy.

[0052] In several exemplary embodiments, as illustrated in Figs. 5a and 5b, the vibratory energy generated by the vibrators 16, 104, 206, 302, 410, and/or 502 of the systems 10, 100, 200, 300, 400, and/or 500 is further controlled to generate vibratory energy that: a) is directed in a plane 500a directed in a longitudinal direction L, and/or a plane 500b directed in a radial direction R, and/or one or more intermediate planes 500c, and/or b) includes center frequencies f_i, where i varies from 1 to N, and/or c) includes one or more, constant and/or variable, center frequencies to thereby enhance the effect of the vibratory energy on one or more of the following: 1) the reduction in the required expansion forces during the radial expansion of the tubular members 18, 208, and/or 408 by the systems, 2) the reduction in contact friction between the expansion cone 14, rotary expansion device 202, and/or expansion cone 404 and the tubular members during the operation of the systems, and/or 3) the increased plasticity of the tubular members during the operation of the systems.

[0053] In an exemplary embodiment, as illustrated in Fig. 6, the systems 10, 100, 200, 300, 400, and/or 500 are operated to determine the operational characteristics of the systems in

accordance with a method 600 in which the plane(s) of the vibratory energy and the frequency and/or energy content of the vibratory energy are set to initial pre-determined values in steps 602 and 604, respectively.

[0054] The system 10, 100, 200, 300, 400, or 500 is then operated and operational characteristics monitored in steps 606 and 608, respectively. In an exemplary embodiment, the operational characteristics that are monitored and recorded in step 608 include the required radial expansion forces, the plane(s) of the vibratory energy, and the frequency and/or energy and/or power content of the vibratory energy.

[0055] The frequency and/or energy and/or power content of the vibratory energy is then incremented in step 610 by a predetermined value. In an exemplary embodiment, in step 610, the frequency and/or energy content and/or power content of the vibratory energy is incremented by: a) adjusting the frequency distribution of the vibratory energy; and/or b) adjusting the magnitude and/or power of the vibratory energy.

[0056] If the incremented frequency and/or energy content of the vibratory energy exceeds a pre-set value in step 612, then the frequency and/or energy and/or power content of the vibratory energy is set to a pre-set initial value in step 614, and the plane(s) of the vibratory energy are incremented by a pre-set amount in step 616. If the incremented plane(s) of the vibratory energy exceeds a pre-set value, then operation ends. Alternatively, If the incremented plane(s) of the vibratory energy does not exceed a pre-set value, then operation proceeds to step 606.

[0057] If the incremented frequency and/or energy and/or power content of the vibratory energy does not exceed a pre-set value in step 612, then operation proceeds to step 606.

[0058] In an exemplary embodiment, the method 600 is implemented to determine the optimal vibrational energy parameters to be used during an expansion operation. In an exemplary embodiment, the optimal vibrational parameters are those parameters that minimize the required radial expansion forces. In an exemplary embodiment, the optimal vibrational energy parameters include one or more of the following: a) vibrational planes; b) frequency distribution of vibrational energy, c) magnitude of the vibrational energy; and/or d) the rate at which the vibrational energy is generated.

[0059] In several alternative embodiments, the vibratory energy generated by the vibrators 16, 104, 206, 302, 410, and/or 502 of the systems 10, 100, 200, 300, 400, and/or 500 is further controlled to generate vibratory energy that imparts rotation to, or affects the rotation of, the expansion cone 14, rotary expansion device 202, and/or the expansion cone 404.

[0060] In several alternative embodiments, one or more of the vibrators 16, 104, 206, 302, 410, and/or 502 of the systems 10, 100, 200, 300, 400, and/or 500 include one or more vibratory elements that impact the tubular members 18, 208, and/or 408.

[0061] In several alternative embodiments, one or more of the vibrators 16, 104, 206, 302, 410, and/or 502 of the systems 10, 100, 200, 300, 400, and/or 500 include one or more vibratory elements that impact the expansion cone 14, rotary expansion device 202, and/or the expansion cone 404.

[0062] In several alternative embodiments, one or more of the vibrators 16, 104, 206, 302, 410, and/or 502 of the systems 10, 100, 200, 300, 400, and/or 500 include one or more vibratory elements that include conventional commercially available agitation devices capable of generating vibratory energy.

[0063] In several alternative embodiments, one or more of the vibrators 16, 104, 206, 302, 410, and/or 502 of the systems 10, 100, 200, 300, 400, and/or 500 include one or more vibratory elements that include conventional commercially available ultrasonic devices capable of generating vibratory energy.

[0064] In several alternative embodiments, one or more of the vibrators 16, 104, 206, 302, 410, and/or 502 of the systems 10, 100, 200, 300, 400, and/or 500 include one or more vibratory elements that include conventional commercially available fluid powered devices capable of generating vibratory energy.

[0065] In several exemplary embodiments, the teachings of the present exemplary embodiments are further implemented in combination with other conventional forms of radial expansion devices such as, for example, impact expansion devices, explosive expansion devices, inflatable expansion devices, and/or impulsive expansion devise to thereby decrease the required expansion forces.

[0066] In several alternative embodiments, the vibrators 16, 104, 206, 302, 410, and/or 502 of the systems 10, 100, 200, 300, 400, and/or 500 are further operated during the insertion and/or removal of the systems from a cased or uncased welbore, or other structure, in order to reduce the frictional forces between the systems and the welbore, or other structural support, during the insertion and/or removal of the systems, thereby enhancing the operational efficiencies of the systems.

[0067] In several alternative embodiments, the operation of the vibrators 16, 104, 206, 302, 410, and/or 502 of the systems 10, 100, 200, 300, 400, and/or 500, before, during, or after the radial expansion and plastic deformation of the tubular members 18, 208, and/or 408 modifies the residual stresses in the tubular members as disclosed and taught in PCT patent application

serial no. PCT/US03/25742, attorney docket no. 25791.117.02, filed on 8/13/2003, which claimed the benefit of the filing date of U.S. provisional patent application serial no. 60/412,177, attorney docket no. 25791.117, filed on 9/20/2002, the disclosures of which are incorporated herein by reference.

[0068] In several alternate embodiments, the exemplary embodiments of Figs. 1-5a and/or the teachings of the present application are implemented using the methods and/or apparatus disclosed in one or more of the following: (1) U.S. patent application serial no. 09/454,139, attorney docket no. 25791.03.02, filed on 12/3/1999, (2) U.S. patent application serial no. 09/510,913, attorney docket no. 25791.7.02, filed on 2/23/2000, (3) U.S. patent application serial no. 09/502,350, attorney docket no. 25791.8.02, filed on 2/10/2000, (4) U.S. patent no. 6,328,113, (5) U.S. patent application serial no. 09/523,460, attorney docket no. 25791.11.02, filed on 3/10/2000, (6) U.S. patent application serial no. 09/512,895, attorney docket no. 25791.12.02, filed on 2/24/2000, (7) U.S. patent application serial no. 09/511,941, attorney docket no. 25791.16.02, filed on 2/24/2000, (8) U.S. patent application serial no. 09/588,946, attorney docket no. 25791.17.02, filed on 6/7/2000, (9) U.S. patent application serial no. 09/559,122, attorney docket no. 25791.23.02, filed on 4/26/2000, (10) PCT patent application serial no. PCT/US00/18635, attorney docket no. 25791.25.02, filed on 7/9/2000, (11) U.S. provisional patent application serial no. 60/162,671, attorney docket no. 25791.27, filed on 11/1/1999, (12) U.S. provisional patent application serial no. 60/154,047, attorney docket no. 25791.29, filed on 9/16/1999, (13) U.S. provisional patent application serial no. 60/159,082, attorney docket no. 25791.34, filed on 10/12/1999, (14) U.S. provisional patent application serial no. 60/159,039, attorney docket no. 25791.36, filed on 10/12/1999, (15) U.S. provisional patent application serial no. 60/159,033, attorney docket no. 25791.37, filed on 10/12/1999, (16) U.S. provisional patent application serial no. 60/212,359, attorney docket no. 25791.38, filed on 6/19/2000, (17) U.S. provisional patent application serial no. 60/165,228, attorney docket no. 25791.39, filed on 11/12/1999, (18) U.S. provisional patent application serial no. 60/221,443, attorney docket no. 25791.45, filed on 7/28/2000, (19) U.S. provisional patent application serial no. 60/221,645, attorney docket no. 25791.46, filed on 7/28/2000, (20) U.S. provisional patent application serial no. 60/233,638, attorney docket no. 25791.47, filed on 9/18/2000, (21) U.S. provisional patent application serial no. 60/237,334, attorney docket no. 25791.48, filed on 10/2/2000, (22) U.S. provisional patent application serial no. 60/270,007, attorney docket no. 25791.50, filed on 2/2012001, (23) U.S. provisional patent application serial no. 60/262,434, attorney docket no. 25791.51, filed on 1/17/2001, (24) U.S. provisional patent application serial no. 60/259,486, attorney docket no. 25791.52, filed on 1/3/2001, (25) U.S. provisional patent

application serial no. 60/303,740, attorney docket no. 25791.61, filed on 7/6/2001, (26) U.S. provisional patent application serial no. 60/313,453, attorney docket no. 25791.59, filed on 8/20/2001, (27) U.S. provisional patent application serial no. 60/317,985, attorney docket no. 25791.67, filed on 9/6/2001, (28) U.S. provisional patent application serial no. 60/318,021, attorney docket no. 25791.58, filed on 9/7/2001, (29) U.S. provisional patent application serial no. 60/3318,386, attorney docket no. 25791.67.02, filed on 9/10/2001, (30) U.S. provisional patent application serial no. 60/326,886, attorney docket no. 25791.60, filed on 1013/2001, (31) U.S. utility patent application serial no. 09/969,922, attorney docket no. 25791.69, filed on 10/3/2001, (32) U.S. provisional patent application serial no. 60/338,996, attorney docket no. 25791.87, filed on 11/12/2001, (33) U.S. provisional patent application serial no. 60/339,013, attorney docket no. 25791.88, filed on 11/12/2001, (34) U.S. utility patent application serial no. 10/016,467, attorney docket no. 25791.70, filed on 12/10/2001, (35) U.S. provisional patent application serial no. 60/343,674, attorney docket no. 25791.68, filed on 12127/2001, (36) U.S. provisional patent application serial no. 60/346,309, attorney docket no 25791.92, filed on 1/712002, (37) U.S. provisional patent application serial no. 601357,372, attorney docket no. 25791.71, filed on 2/15/2002, (38) U.S. provisional patent application serial no. 60/363,829, attorney docket no. 25791.95, filed on 3/1312002, (39) U.S. provisional patent application serial no. 60/372,048, attorney docket no. 25791.93, filed on 4/12/2002, (40) U.S. provisional patent application serial no. 60/372,632, attorney docket no. 25791.101, filed on 4/15/2002, (41) U.S. provisional patent application serial no. 60/380,147, attorney docket no. 25791.104, filed on 5/6/2002, (42) U.S. provisional patent application serial no. 60/383,917, attorney docket no. 25791.89, filed on 5/2912002, (43) U.S. provisional patent application serial no. 60/387,486, attorney docket no. 25791.107, filed on 6/10/2002, (44) U.S. provisional patent application serial no. 60/387,961, attorney docket no. 25791.108, filed on 611212002, (45) U.S. provisional patent application serial no. 60/391,703, attorney docket no. 25791.90, filed on 6/26/2002, (46) U.S. provisional patent application serial no. 60/397,284, attorney docket no. 25791.106, filed on 7/19/2002, (47) U.S. provisional patent application serial no. 60/398,061, attorney docket no. 25791.110, filed on 7/24/2002, (48) U.S. provisional patent application serial no. 60/399,240, attorney docket no. 25791.111, filed on 7/2912002, (49) U.S. provisional patent application serial no, 601405,610, attorney docket no. 25791.119, filed on 8/2312002, (50) U.S. provisional patent application serial no. 60/405,394, attorney docket no. 25791.120, filed on 8/2312002, (51) U.S. provisional patent application serial no. 60/407,442, attorney docket no. 25791.125, filed on 8/30/2002, (52) U.S. provisional patent application serial no. 60/412,542, attorney docket no. 25791.102, filed on 9/20/2002, (53) U.S. provisional patent application serial no.

60/412,177, attorney docket no. 25791.117, filed on 9/20/2002, (54) U.S. provisional patent application serial no. 601412,653, attorney docket no. 25791.118, filed on 9/20/2002, (55) U.S. provisional patent application serial no. 601412,544, attorney docket no. 25791.121, filed on 9/20/2002, (56) U.S. provisional patent application serial no. 60/412,187, attorney docket no. 25791.128, filed on 9/20/2002, (57) U.S. provisional patent application serial no. 60/412,196, attorney docket no. 25791.127, filed on 9/20/2002, (58) U.S. provisional patent application serial no. 60/412,487, attorney docket no. 25791.112, filed on 9/20/2002, (59) U.S. provisional patent application serial no. 601412,488, attorney docket no. 25791.114, filed on 9/20/2002, (60) U.S. provisional patent application serial no. 60/412,371, attorney docket no. 25791.129, filed on 9/20/2002, (61) PCT patent application serial no. PCT/US02/36157, attorney docket no. 25791.87.02, filed on 11/12/2002, and (62) PCT patent application serial no. PCT/US02/36267, attorney docket no. 25791.88.02, filed on 11/12/2002, the disclosures of which are incorporated herein by reference.

[0069] In several exemplary embodiments, the teachings of the present exemplary embodiments may be used, for example, to provide or repair a wellbore casing, a pipeline, an underground pipeline, and/or a structural support. Furthermore, the teachings of the present exemplary embodiments related to the use of vibration to facilitate and enhance the formability of expandable tubular members may find application to other types of radial expansion and plastic deformation processes such as, for example, hydroforming and/or explosive forming of expandable tubulars.

[0070] An apparatus for radially expanding and plastically deforming an expandable tubular member has been described that includes an expansion device movable in the expandable tubular member for radially expanding and plastically deforming the expandable tubular member; and a vibratory device coupled to the expansion device for generating vibratory energy to agitate at least one of the expandable tubular member and the expansion device. In an exemplary embodiment, the expansion device comprises: a tapered expansion cone. In an exemplary embodiment, the expansion device further comprises: an actuator coupled to the tapered expansion cone for displacing the tapered expansion cone in an axial direction relative to the expandable tubular member. In an exemplary embodiment, the expansion device further comprises: a locking device coupled to the actuator for fixing the position of the expandable tubular member relative to the actuator during the axial displacement of the expansion cone relative to the expandable tubular member. In an exemplary embodiment, the expansion device comprises: a rotary expansion device. In an exemplary embodiment, the vibratory device is positioned within a non-expanded portion of the expandable tubular member. In an exemplary

embodiment, the vibratory device is positioned within an expanded portion of the expandable tubular member. In an exemplary embodiment, the vibratory device is positioned within the expansion device. In an exemplary embodiment, the vibratory device comprises a plurality of vibratory devices. In an exemplary embodiment, at least one of the vibratory devices is positioned within a non-expanded portion of the expandable tubular member. In an exemplary embodiment, at least another one of the vibratory devices is positioned within an expanded portion of the expandable tubular member. In an exemplary embodiment, at least another one of the vibratory devices is positioned within the expansion device. In an exemplary embodiment, at least another one of the vibratory devices is positioned within the expansion device. In an exemplary embodiment, at least one of the vibratory devices is positioned within an expanded portion of the expandable tubular member. In an exemplary embodiment, at least another one of the vibratory devices is positioned within the expansion device. In an exemplary embodiment, at least another one of the vibratory devices is positioned within the expansion device. In an exemplary embodiment, the vibratory device comprises: a fluid powered vibratory device. In an exemplary embodiment, the vibratory energy comprises: vibratory energy in one or more planes. In an exemplary embodiment, the vibratory energy comprises: vibratory energy having a frequency distribution having one or more center frequencies. In an exemplary embodiment, the vibratory energy comprises: vibratory energy having a frequency distribution having a plurality of center frequencies. In an exemplary embodiment, the vibratory energy comprises: vibratory energy in a plurality of planes. In an exemplary embodiment, the vibratory energy comprises: vibratory energy having a frequency distribution having one or more center frequencies. In an exemplary embodiment, the vibratory energy comprises: vibratory energy having a frequency distribution having a plurality of center frequencies. In an exemplary embodiment, the vibratory energy comprises: vibratory energy having a frequency distribution having one or more center frequencies. In an exemplary embodiment, the vibratory energy comprises: vibratory energy having a frequency distribution having a plurality of center frequencies. In an exemplary embodiment, the magnitude of the vibratory energy is variable. In an exemplary embodiment, the magnitude of the vibratory energy is constant. In an exemplary embodiment, the plane of the vibratory energy is variable. In an exemplary embodiment, the plane of the vibratory energy is constant. In an exemplary embodiment, the expandable tubular member comprises a welbore casing. In an exemplary embodiment, the expandable tubular member comprises a pipeline. In an exemplary embodiment, the expandable tubular member comprises a structural support. In an exemplary embodiment, the vibratory device coupled to the expansion device generates vibratory energy to agitate the expandable tubular member and

the expansion device. In an exemplary embodiment, the apparatus further comprises: a vibratory device coupled to the expansion device for generating vibratory energy to impart rotation to the expansion device. In an exemplary embodiment, the vibratory device is adapted to impact the expandable tubular member. In an exemplary embodiment, the vibratory device is adapted to impact the expansion device.

[0071] A method of radially expanding and plastically deforming an expandable tubular member has been described that includes radially expanding and plastically deforming the expandable tubular member using an expansion device; and injecting vibratory energy into at least one of the expandable tubular member and the expansion device. In an exemplary embodiment, the method further comprises: displacing the expansion device in an axial direction relative to the expandable tubular member during the radial expansion and plastic deformation. In an exemplary embodiment, the method further comprises: fixing the position of the expandable tubular member relative to the expansion device during the axial displacement of the expansion device relative to the expandable tubular member. In an exemplary embodiment, the method further comprises: rotating the expansion device during the radial expansion and plastic deformation of the expandable tubular member. In an exemplary embodiment, the vibratory energy is injected from a location within a non-expanded portion of the expandable tubular member. In an exemplary embodiment, the vibratory energy is injected from a location within an expanded portion of the expandable tubular member. In an exemplary embodiment, the vibratory energy is injected for a location within the expansion device. In an exemplary embodiment, the vibratory energy is injected from a plurality of locations. In an exemplary embodiment, at least some portion of the vibratory energy is injected from a location within a non-expanded portion of the expandable tubular member. In an exemplary embodiment, at least another portion of the vibratory energy is injected from a location within an expanded portion of the expandable tubular member. In an exemplary embodiment, at least another portion of the vibratory energy is injected from a location within the expansion device. In an exemplary embodiment, at least another portion of the vibratory energy is injected from a location within the expansion device. In an exemplary embodiment, at least some portion of the vibratory energy is injected from a location within an expanded portion of the expandable tubular member. In an exemplary embodiment, at least another portion of the vibratory energy is injected from a location within the expansion device. In an exemplary embodiment, at least a portion of the vibratory energy is injected from a location within the expansion device. In an exemplary embodiment, injecting vibratory energy into at least one of the expandable tubular member and the expansion device comprises: injecting fluidic materials into the expandable

tubular member. In an exemplary embodiment, the vibratory energy comprises: vibratory energy in one or more planes. In an exemplary embodiment, the vibratory energy comprises: vibratory energy having a frequency distribution having one or more center frequencies. In an exemplary embodiment, the vibratory energy comprises: vibratory energy having a frequency distribution having a plurality of center frequencies. In an exemplary embodiment, the vibratory energy comprises: vibratory energy in a plurality of planes. In an exemplary embodiment, the vibratory energy comprises: vibratory energy having a frequency distribution having one or more center frequencies. In an exemplary embodiment, the vibratory energy comprises: vibratory energy having a frequency distribution having a plurality of center frequencies. In an exemplary embodiment, the vibratory energy comprises: vibratory energy having a frequency distribution having one or more center frequencies. In an exemplary embodiment, the vibratory energy comprises: vibratory energy having a frequency distribution having a plurality of center frequencies. In an exemplary embodiment, the magnitude of the vibratory energy is variable. In an exemplary embodiment, the magnitude of the vibratory energy is constant. In an exemplary embodiment, the plane of the vibratory energy is variable. In an exemplary embodiment, the plane of the vibratory energy is constant. In an exemplary embodiment, the expandable tubular member comprises a welbore casing. In an exemplary embodiment, the expandable tubular member comprises a pipeline. In an exemplary embodiment, the expandable tubular member comprises a structural support. In an exemplary embodiment, the method further comprises: injecting vibratory energy into the expandable tubular member and the expansion device. In an exemplary embodiment, the method further comprises: injecting vibratory energy into the expansion device to impart rotation to the expansion device. In an exemplary embodiment, injecting vibratory energy into at least one of the expandable tubular member and the expansion device, comprises: impacting the expandable tubular member. In an exemplary embodiment, injecting vibratory energy into at least one of the expandable tubular member and the expansion device, comprises: impacting the expansion device.

[0072] A system for radially expanding and plastically deforming an expandable tubular member has been described that includes means for radially expanding and plastically deforming the expandable tubular member using an expansion device; and means for injecting vibratory energy into at least one of the expandable tubular member and the expansion device. In an exemplary embodiment, the further comprises: means for displacing the expansion device in an axial direction relative to the expandable tubular member during the radial expansion and plastic deformation. In an exemplary embodiment, the system further comprises: means for fixing the position of the expandable tubular member relative to the means for displacing the

expansion device during the axial displacement of the expansion device relative to the expandable tubular member. In an exemplary embodiment, the system further comprises: means for rotating the expansion device during the radial expansion and plastic deformation of the expandable tubular member. In an exemplary embodiment, the vibratory energy is injected from a location within a non-expanded portion of the expandable tubular member. In an exemplary embodiment, the vibratory energy is injected from a location within an expanded portion of the expandable tubular member. In an exemplary embodiment, the vibratory energy is injected for a location within the expansion device. In an exemplary embodiment, the vibratory energy is injected from a plurality of locations. In an exemplary embodiment, at least some portion of the vibratory energy is injected from a location within a non-expanded portion of the expandable tubular member. In an exemplary embodiment, at least another portion of the vibratory energy is injected from a location within an expanded portion of the expandable tubular member. In an exemplary embodiment, at least another portion of the vibratory energy is injected from a location within the expansion device. In an exemplary embodiment, at least another portion of the vibratory energy is injected from a location within the expansion device. In an exemplary embodiment, at least some portion of the vibratory energy is injected from a location within an expanded portion of the expandable tubular member. In an exemplary embodiment, at least another portion of the vibratory energy is injected from a location within the expansion device. In an exemplary embodiment, at least a portion of the vibratory energy is injected from a location within the expansion device. In an exemplary embodiment, injecting vibratory energy into at least one of the expandable tubular member and the expansion device comprises: injecting fluidic materials into the expandable tubular member. In an exemplary embodiment, the vibratory energy comprises: vibratory energy in one or more planes. In an exemplary embodiment, the vibratory energy comprises: vibratory energy having a frequency distribution having one or more center frequencies. In an exemplary embodiment, the vibratory energy comprises: vibratory energy having a frequency distribution having a plurality of center frequencies. In an exemplary embodiment, the vibratory energy comprises: vibratory energy in a plurality of planes. In an exemplary embodiment, the vibratory energy comprises: vibratory energy having a frequency distribution having one or more center frequencies. In an exemplary embodiment, the vibratory energy comprises: vibratory energy having a frequency distribution having a plurality of center frequencies. In an exemplary embodiment, the vibratory energy comprises: vibratory energy having a frequency distribution having one or more center frequencies. In an exemplary embodiment, the vibratory energy comprises: vibratory energy having a frequency distribution having a plurality of center frequencies. In an exemplary

embodiment, the magnitude of the vibratory energy is variable. In an exemplary embodiment, the magnitude of the vibratory energy is constant. In an exemplary embodiment, the plane of the vibratory energy is variable. In an exemplary embodiment, the plane of the vibratory energy is constant. In an exemplary embodiment, the expandable tubular member comprises a welbore casing. In an exemplary embodiment, the expandable tubular member comprises a pipeline. In an exemplary embodiment, the expandable tubular member comprises a structural support. In an exemplary embodiment, the system further comprises: means for injecting vibratory energy into the expandable tubular member and the expansion device. In an exemplary embodiment, the system further comprises: means for injecting vibratory energy into the expansion device to impart rotation to the expansion device. In an exemplary embodiment, means for injecting vibratory energy into at least one of the expandable tubular member and the expansion device, comprises: means for impacting the expandable tubular member. In an exemplary embodiment, means for injecting vibratory energy into at least one of the expandable tubular member and the expansion device, comprises: means for impacting the expansion device. In an exemplary embodiment, the method further comprises: inserting the expansion device and the expandable tubular member into a preexisting structure; and injecting vibratory energy into at least one of the expandable tubular member and the expansion device during the insertion. In an exemplary embodiment, the method further comprises: removing the expansion device and the expandable tubular member from a preexisting structure; and injecting vibratory energy into at least one of the expandable tubular member and the expansion device during the removal.

[0073] A system for radially expanding and plastically deforming an expandable tubular member has been described that comprises: means for radially expanding and plastically deforming the expandable tubular member; and means for reducing the required radial expansion forces during the radial expansion and plastic deformation of the expandable tubular member.

[0074] Although illustrative embodiments have been shown and described, a wide range of modification, change and substitution is contemplated in the foregoing disclosure and in some instances, some features of the embodiments may be employed without a corresponding use of other features. Accordingly, it is appropriate that the appended claims be construed broadly and in a manner consistent with the scope of the embodiments disclosed herein.